CODE TESLA FOR MODELING AND DESIGN OF HIGH-POWER HIGH-EFFICIENCY KLYSTRONS*

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Abstract

This work gives an overview of the main features of the 2.5D large-signal code TESLA and its capabilities for the modelling single-beam and multiple-beam klystrons as high-power RF sources. These sources are widely used or proposed to be used in accelerators in the future. Comparison of TESLA modelling results with experimental data for a few multiple-beam klystrons are shown.

INTRODUCTION

High-power and high-efficiency klystrons are widely used in accelerators as RF power sources. Design and optimization of klystrons requires efficient simulation tools. One such tool is the code TESLA, which currently is used in NRL and in a few large US tube companies.

TESLA (Telegraphist's Equations Solution for Linear-beam Amplifiers) is a 2.5D large-signal code successfully applied to the modeling of single beam and multiple beam amplifiers having linear propagating beams. TESLA evolved from the code MAGY [1] and was developed [2] as a result of collaboration of NRL, SAIC and the University of Maryland. This code was initially implemented for the purpose of modeling devices with external resonance cavities, and was applied first to the simulation of conventional single-beam klystrons. Further extensive development added in the code capability to model a wide range of linear-beam amplifiers, including multiple-beam klystrons (MBKs), extended interaction klystrons (EIKs) and inductive output tubes (IOTs). Recently the code was modified to allow modelling of coupled cavity travelling-wave tubes (CCTWTs) as well.

The TESLA model is designed to describe accurately self-consistent large-signal beam-wave interaction. It includes self-consistent solution of the three-dimensional equations of electron motion and the time-dependent field equations. TESLA is a hybrid code that exploits the idea of having separate representations of the fields inside the beam-tunnel and in external resonant cavities. It combines a simplified model for the fields of external cavities with a modal decomposition of RF fields in the beam tunnel.

The TESLA model uses a slow timescale approximation, in which the complex amplitudes of the modes appearing in the Telegraphist's equations for the beam tunnel evolve slowly compared to the RF period. The electron beam in TESLA is represented as an ensemble of macro-particles, for which trajectory are computed using fully relativistic equations of motion for a charged particle in an electromagnetic field. As the RF field amplitudes are assumed to vary slowly during the transit time of the particles, the full trajectories are computed once per time-step of the fields. In addition, the particle trajectories are assumed periodic with respect to the entrance time at the RF wave frequency, so that the ensemble of particles only needs to represent a single period of the entrance phase.

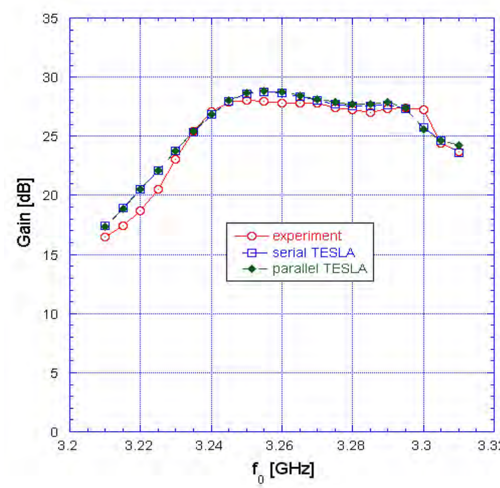

Figure 1: Comparison of predictions of serial and parallel versions of the code TESLA with the measured large-signal gain of the NRL fundamental mode 4-cavity 8-beam MBK1 [3].

The current implementation of TESLA is based on the Fortran-95 language and takes advantage of the modular programming technique together with highly efficient, dynamical use of the computer memory. On average, TESLA runs were found to be ~2 orders of magnitude faster than the typical run of a fully 3D PIC code. Advanced performance of TESLA together with its user-friendly Python-based GUI and set of post-processing tools makes the TESLA package very useful as a primary design tool. Results presented in Fig.1 illustrate that TESLA predictions are in good agreement with the experiment.

Among other important features of the code there are also capabilities: 1) to take into account AC and DC space-charge effects; 2) to use pre-defined models for the particles' initialization or import an arbitrary distribution, given by a gun-code; 3) to use a pre-defined or import an arbitrary 1D or 2D magnetic field profile; 4) to use a predefined or import an arbitrary gap-field profile.

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14. ABSTRACT
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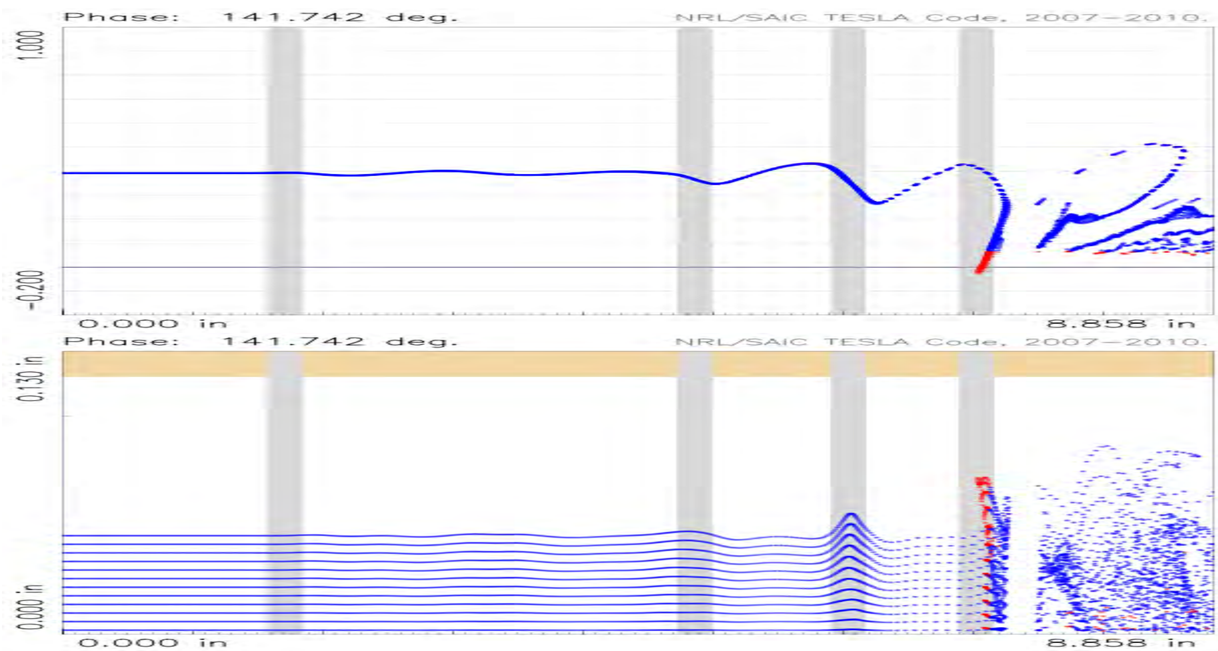

Figure 2: Phase space (top) and trajectories (bottom) of TESLA macro-particles shown for the 4-cavity 8-beams NRL MBK1 [3] simulated here in the approximation of the identical beams and beam-tunnels. Slow particles are shown here by a different color.

TESLA MODELING OF KLYSTRONS

TESLA model achieves numerical efficiency in part because it uses equations of motion in a representation which considers *z* as independent variable. Such approach allows easy particle trajectory integration and accumulation of sources on an axial grid; also, all particles having different entrance times can be integrated together. However, this approach is eligible only as long as an electron's axial position increases monotonically as it passes through the device. But this can be not the case in high-power, high-efficiency klystrons, which typically create such strong RF fields that they can greatly slow down or even reverse an electron's axial motion. As we have a division by the electron's axial velocity in such equations of motion, then we will have problems with their use.

TESLA model was extended [4] to handle properly particles for which the axial velocity falls below some "critical" threshold. Once a particle's axial velocity was found below this threshold, the code starts to consider it as a "special" particle and integrates it by following in time, considering now *t* as independent variable. This approach is completely free from the above mentioned problems and allows an improved TESLA algorithm to cover now all possible types of particle trajectories in klystrons, including such cases when a particle's motion was partially or completely reversed. Partial reversal of particle trajectories can be frequently observed in the vicinity of the gap of the output cavity of high-efficiency klystrons (see phase-space on the Fig.2); typically such particle will be re-accelerated back to the exit, once the phase of the RF field will change sign. In the case of a particle's full reflection, it was verified by comparison with the PIC code MAGIC-2D that TESLA is now capable of accurately predicting the threshold for the particle's reflection and track its trajectory back to the entry of the device [4].

The 2D nature of the TESLA modelling is illustrated in Fig,2 by showing particle trajectories as functions of their radii versus axial coordinates. Note that the active transverse motion of particles happens in the vicinity of the output cavity, where they potentially can hit the wall. The capability of the code to predict the interception current became one of its very important features.

ADVANCED TESLA MODELING: MBK, EIK AND IOT

An extension of the serial version of TESLA allowed modelling of multiple-beam klystrons with the assumption of identical beams/beam-tunnels, and was applied by using an averaging of the R/Qs over all beam-tunnels. In general, this was found to be a very good approximation (Fig.1). However, the real multiple-beam device can have significant variations of parameters from beam-tunnel to beam-tunnel. To take this into account and to find possible effects of such variations, TESLA was transformed into a parallel version [5] that enables us to model multiple non-identical beams/beam-tunnels in separate parallel processes, communicating with each other using MPI-calls.

The parallel version of TESLA was successfully applied to model the NRL experimental fundamental mode 4-cavity 8-beam MBK1 [3], having a large spread in the values of R/Q inside the different beam-tunnels of the resonant cavities, which was especially pronounced

in the output cavity of the device (Table III in [5]). The appearance and rise of the interception current inside the 4 inner beam-tunnels of MBK1 (curve 2 on Fig.3) predicted by the parallel code was found in good agreement with the experimentally observed drop in the beam-transmission (curve 1) starting from P_{in} ~700W.

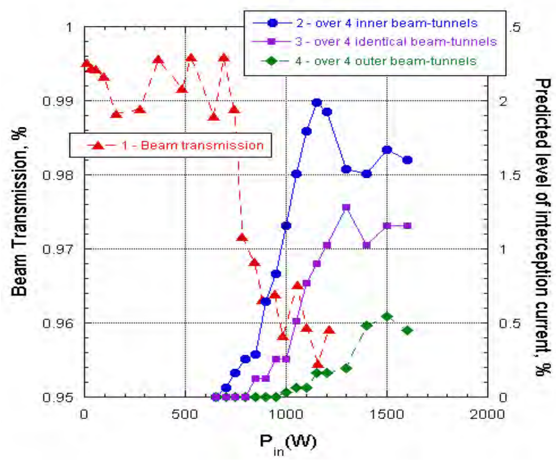

Figure 3: Experimental beam-transmission (curve 1) and interception current per group, predicted by TESLA, for inner (2) and outer (4) beam-tunnels of MBK1 [3].

Another important extension of the TESLA model is its capability of accurate modelling of beam-wave interaction in multi-gap resonators. It allows successfully accommodate the features of cavities designed for broadband and high-gain interaction in MBKs [6] and EIKs [7].

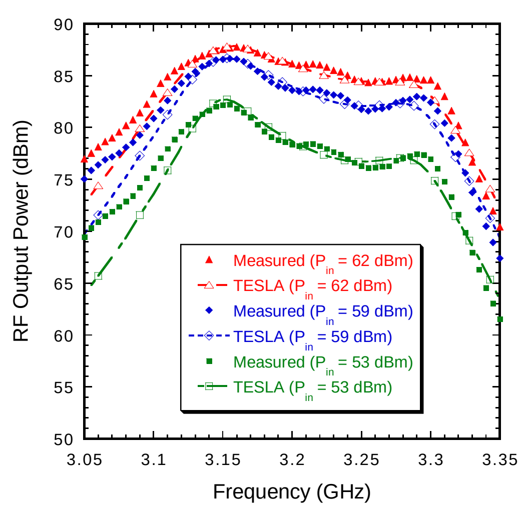

Figure 4: Comparison of experimental and predicted by TESLA bandwidth of the wide-band NRL MBK2 [6] at a few drive powers.

Figure 4 shows good agreement between the results of TESLA simulations and the measurements for the NRL broadband MBK2 device [6], utilizing multiple-gaps and coupled resonators together with their asymmetrical loading.

Capability of the code TESLA to utilize pre-bunched beam allows also extend its applicability on the modeling of IOT type devices (Fig.5), based on the use of the density modulated beams.

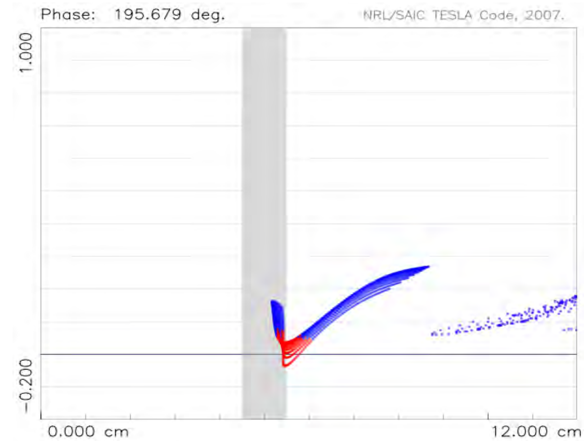

Figure 5: Simulated by TESLA phase-space of the pre-modulated electron beam in the vicinity of an output cavity of IOT.

Ability of the code to work with an arbitrary beam's configurations, imported from a gun code, together with a few particles' depopulation algorithms, makes it especially useful for taking into account such fine effects as the thermal spreads and temporal evolution of particles on entrance into the simulation region.

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